MRD-451 & 452
Polarimetry & Astrometry

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MRD-451: Extended Source Polarimetric Accuracy

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MRD-451: Polarimetric Astrometric Accuracy

MRD-451 The Coronagraph Instrument shall be able to map the linear polarization of a circumstellar debris disk that has a polarization fraction greater or equal to 0.3 with an uncertainty of less than 0.03 in CGI Filter Band 1 and CGI Filter Band 4, assuming SNR of 100 per resolution element.

1) Science:

- **Polarized fraction probes grain size and properties.**

2) Engineering challenges:

- **Raw Contrast must be comparable in both polarization states, as well as in total intensity (wavefront control)**
- **Polarizer leak must be < 1% (TBR) (polarizer manufacture)**
- **Polarizer angle must be precise and repeatable to better than 1 degree (TBR) (polarizer installation & calibration)**
- **CGI IP must not change by more than 1% between calibration target, reference star, and science target (optics & wavefront control)**
- Note: No fundamental differences between challenges in Band 1 vs. Band 4.

Polarimetry: methodology

- $I_Q = (I_{90} - I_0)$
- $I_U = (I_{135} - I_{45})$
- $I_{tot} = ½ (I_0 + I_{45} + I_{90} + I_{135})$
- **Polarized fraction** $= (I_Q^2 + I_U^2)^{1/2} / I_{tot}$

- If each I_θ has SNR=100, then uncertainty on each polarized fraction is <1%.

- **Challenges:**
  - Systematic effects of PSF subtraction data processing of total intensity disk images.
  - Systematic differences in RDI post-processed speckle field between orthogonal polarization states.

- **Calibration concern: Instrumental polarization**
  - Need well-characterized polarimetric standards.
  - Time variability should be < 1 % Will be evaluated in Phase B.

Polarimetry: dark hole digging

Current baseline is to dig dark hole in unpolarized light:

- Use same DM solution for unpolarized light and for each polarization state.
- Fastest option, because only dig hole once, and use all photons. However, dark hole is not optimized for each polarization state.

- **Systematic differences in speckle field between orthogonal polarization states. Modeling suggests:**
  - RDI post-processed speckle field difference between orthogonal polarizations is **less than a factor of 2**
  - Non-common path WFE introduced by polarizers is negligible, because they are behind the lenslet array and lyot stop (tolerance on WFE of polarizers will be setin Phase B)

- **in Phase B:** Evaluate whether SNR gain for polarimetry justifies digging a dark hole for each polarization independently

Polarimetry: current challenges

- **Systematic biases of PSF subtraction on extended emission.**
  - High SNR disks will not need aggressive processing.
  - Disk-optimized techniques, RDI, and/or “Forward modeling” of disks are have all been used in the literature [eg: 1] & will be explored further in Phase B

- **Instrumental polarization:**
  - GPI has an average IP < 0.5%, with <0.1% variability [2]
  - Need well-characterized polarimetric standards.

[1] Ren, B., et al., 2018, ApJ, 852, 104

[2] Millar-Blanchaer, M., et al., 2016, Proc. SPIE, 9908, 990836

MRD-452: Exoplanet Astrometric Accuracy

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MRD-452: Exoplanet Astrometric Accuracy

MRD-452: The Coronagraph Instrument shall be able to measure the relative astrometry between an astrophysical point source and its host star, in photometric images, for separations from 0.21 arcsec to 1.36 arcsec, with an accuracy of 5 milliarcsec or less, assuming SNR of 10 or greater, including systematic errors.

Astrometry in WFIRST CGI serves two purposes:

1) Science:

- Whether an object is bound or not
- What the object's orbital parameters are
- How extended objects relate to their parent star (e.g. disks decentered from parent stars)
- Parallax and proper motion of system to estimate distance and galactic motion

2) Engineering:

a) Where the star is on the detector (for acquisition and alignment).

b) Where a speckle is with respect to the star center (for wavefront control)

c) Wedges on engineering filters will shift the star to a different location per band

Note: Plate scale calibration is not photon-limited.

Imager: 5mas = 0.24 pixel

IFS: 5mas = 0.19 pixel (worst-case)

Astrometry: challenges

- **Fundamental measurement limit: (planet FWHM) / (sqrt(2) * planet SNR)**
  - **575nm**: (λ/D) = 49 mas => **SNR >= 7** is required
  - **866nm**: SPC disk FWHM = 66 mas=> **SNR >= 10** is required for 5mas precision

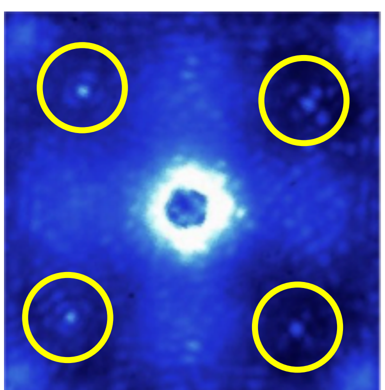
- **Two regimes for planet astrometry:**
  - High SNR planet: **systematics >>** (planet FWHM) / (planet SNR)
  - Low SNR planet: systematics **<< (planet FWHM) / (planet SNR)**

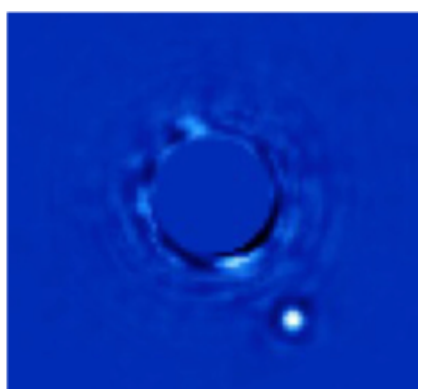
- **Other Challenges:**
  - Measure star location (behind coronagraph) in each image.
  - Remove systematic effects of data processing on planet PSF.

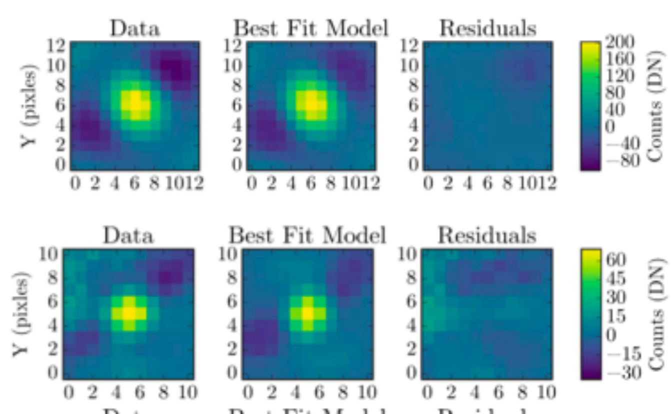
- **Calibration concerns: Plate scale and detector orientation**
  - North angle known to < 0.1 dgr (5mas / 1.3” = 0.21 dgr).
  - Plate scale known to < 0.2% (5mas / 1.3” = 0.38%).
  - Need a well-studied astrometric calibrator with appropriate separation and flux ratio.

Astrometry: current state of the art

- **1mas precision is possible with current ground-based instrumentation**
- **Gemini Planet Imager Coronagraphic H-band IFS measurements of β Pictoris**
  - *Wang, J. J., et al., 2016, AJ, 152, 97, "The orbit and transit prospects for β Pictoris b constrained with one milliarcsecond astrometry"*
  - 1 mas ~ 0.07 GPI pixels
  - 4 "Satellite spots" created by a pupil plane (intensity) mask are used to measure the location of the primary star in every coronagraphic IFS image. Images co-centered before further processing.
  - Initial guess at planet location using centroid (~1px accuracy).
  - Improve by cross-correlating with a model of planet PSF and spectrum. (Run a "matched filter" on a PSF that includes a "forward model" of distortion/self-subtraction due to data processing).
  - Astrometry in high planet SNR epochs was limited by knowledge of primary star location and/or plate scale & orientation, **NOT** by planet (x,y) location measurement.







Astrometry: engineering (1 of 2)

Current baseline is centroiding with automatic peak selection:

- **Provide coarse peak location, window size.**
- **Refine the peak location (peak pixel within coarse window)**
- **Do a centroid over the re-centered window.**

Fast, simple, subpixel results, and fairly insensitive to starting point but vulnerable to biases due to window size selection, and has some sensitivity to cosmic rays and other

Tests with disk-mask images:

- **[0.059, 0.057] pixel systematic bias per axis from window size (40 pixels to 60 pixels)**
- **0.052 pixel repeatability 1σ (RSSed over both axes) over 30 sequential images**

Extend with satellite spots:

- **One or more pairs of sine waves with the DM, apply with positive, negative and zero amplitude, and process as $(I_+ + I_-)/2 - I_0$ to get peaks independent of the underlying field.**
- **Star will be centered between any two associated peaks from a sine.**
- **Usable while the star is occulted without removing the focal-plane mask, and consistent with any of the above requirements. Used regularly in HCIT.**

Astrometry: engineering (2 of 2)

Possible extension: cross-correlation

- **Correlate an image of the peak, then use peak map as centroiding input**
- **Less sensitive to windowing errors, noise, and cosmic rays but**
  - requires an accurate peak (or peak model) with good clocking
  - only gets pixel accuracy; needs to be combined with a centroid or other subpixel fit to get better
- **With disk-mask images: 0.044 pixel repeatability 1σ (RSSed over both axes) over 30 sequential images**
  - Uses centroiding with peak selection on correlation maps

Other options (in current HCIT software)

- **Fourier shifting: Fourier transform of a phase tilt is an image shift.**
  - Transform, apply a tilt, transform back, and wrap this in a fitting routine to get sub-pixel location. Requires a decent initial starting point.
- **Peak fitting: Given a raw image or a cross-correlation map, fit a smooth, singly-peaked function (e.g. a Gaussian or parabola) to region of peak pixel.**
  - Subpixel location of maximum gives center

Astrometry: suggested CGI procedure

- **Measure star location in every frame:**
  - "Satellite spots" generated by DM sinewaves used to measure the location of the primary star while occulted by the coronagraph **before** science sequence begins. Satellite spot brightness chosen such that FWHM / SNR < 1 mas. LOWFS star position is recorded concurrently.
  - LOWFS tracks & corrects star position through science sequence. Position of star from LOWFS is recorded with every science frame to at least 0.5 mas accuracy (CGI-TECH-8).

- **Measure the planet position in the final frame:**
  - Initial guess at planet location using centroid.
  - Improved estimation with cross-correlation, Fourier filtering, forward model / matched filtering, or other algorithm. Will be tested in Phase B with simulated images.

- **Known plate scale and North orientation of every image**
  - Orientation of spacecraft of spacecraft is controlled to better than 0.1dgr (TBR)
  - Plate scale and orientation of CGI with respect to the telescope should be calibrated every (TBR) days, tied to recent observations from well-calibrated observatories.
    - Current ground-based high-contrast imagers have typical uncertainties of ~0.1 dgr and <0.1% in plate scale.
    - Astrometric standards should be calibrated close in time to CGI observations, so that orbital motion of stars in binary systems is negligible.